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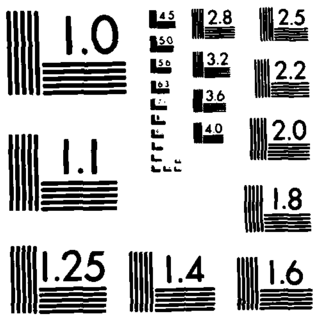

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The induction Linac program has been carried out principally using a dedicated Blumlein facility as the pulse power source. As previously described the source feeds a two to one step up autotransformer, which when coupled with a direct electrostatic feed to the anode from the Blumlein, gives a diode voltage of three times the line output voltage. The nominal operating impedance of the system is 21 Ohms. This system has continued to work well during the current grant period.

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I. Introduction

A brief summary of research carried out under grant # AFOSR-83-0364, during the period 30 Sept. 1983 to 29 Sept 1984 is presented. The technical summary is divided into three parts, one describing the equipment status, the second part concerned with diagnostic development, and the third with specific aspects of our study of proton acceleration. The report also lists papers and conference reports arising from this work.

II Progress Report

A. Equipment Status.

The Induction Linac program has been carried out principally using a dedicated Blumlein facility as the pulse power source. As previously described the source feeds a two to one step up autotransformer, which when coupled with a direct electrostatic feed to the anode from the Blumlein, gives a diode voltage of three times the line output voltage. The nominal operating impedance of the system is 21 Ohms. This system has continued to work well during the current grant period.

We have investigated two procedures for increasing the proton beam energy in the Linac. The first alternative considered was to use an autoaccelerator configuration described in a previous report. This was rejected as a result of an inherent 18 nsec. delay found in the operation of the accelerator. The delay appears between application of the pulse to the primary of the autoaccelerator and the onset of the output pulse. Each transit of the autoaccelerator cores leads to an additional 9 nsec. delay. The delay is due to the penetration time of the electromagnetic fields into the ferrite cores. The 18 nsec. delay required in the autoacceleration approach to increasing the proton beam energy is too long in view of the short proton pulse length. The inherent delay described and measured here indicates a fundamental limitation on the useful pulse lengths and rise times achievable with ferrite core systems. The second approach considered was to employ an externally driven acceleration gap. This was the approach adopted. A xerox copy of a photograph of the assembly is shown on the next page. The second gap is driven by a tap off from the primary Blumlein source. The impedance

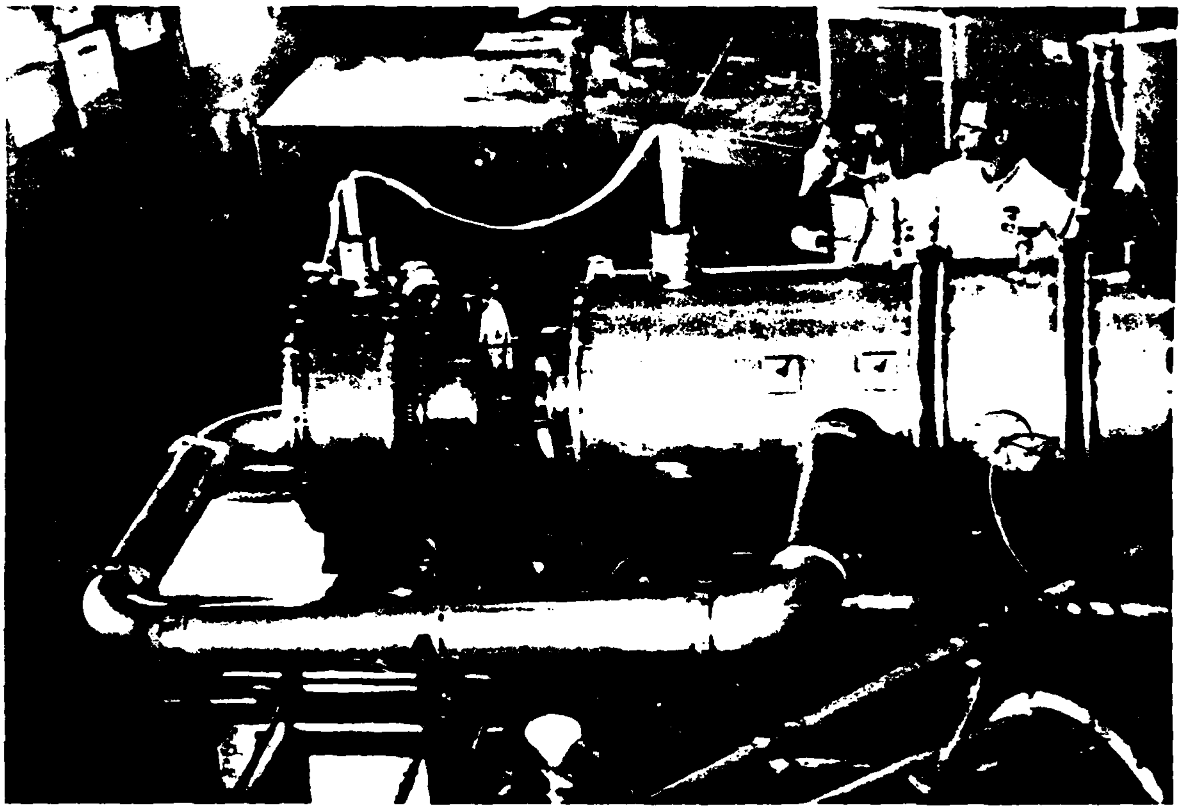

FIGURE 1. PHOTOGRAPH OF ASSEMBLY

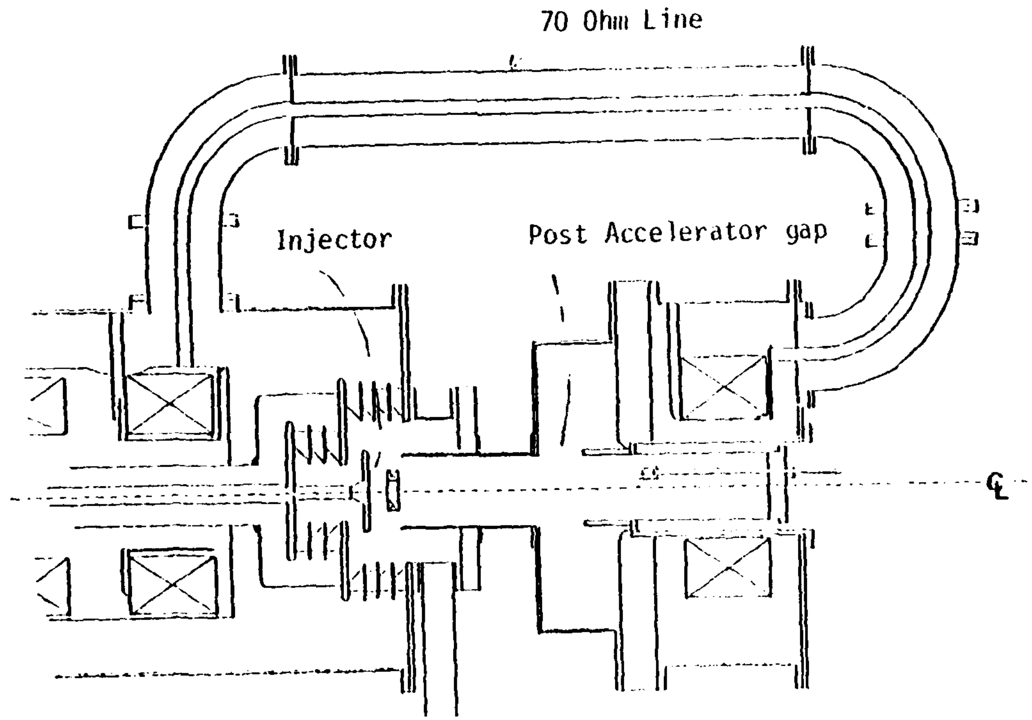

FIGURE 2 Induction Accelerator Schematic

of the connection cable is approximately 70 Ohms and hence does not place an undue load on the primary while still allowing sufficient current to flow to drive the main beam. The connecting cable length is chosen to match the transit time of the 1.1 MeV protons from the source diode. This configuration is convenient for our operation as it provides all of the essential features required for our investigation of a multi-stage Induction Linac without having, at this stage at least, the additional concerns associated with time synchronization of the accelerator pulses. We show in the second figure a schematic illustrating the composite assembly. The proton beam is transported between the successive acceleration gaps through a vacuum drift region along a strong 16-20 kGauss magnetic field. Electron flow is suppressed in the acceleration regions by radial magnetic fields. More detail on the field design will be found in the technical progress section of this report. Figure three shows traces of oscilloscope records of the post acceleration gap voltage and current. Note that any mismatch of the postacceleration gap impedance with the feed line does not cause any problems in the source diode since the round trip time of the electromagnetic wave in the feed is greater than the pulse length.

B. Diagnostic Development.

During the past contract period we have focussed much of our attention on the development of time resolved diagnostic techniques for the proton beam. In particular we have spent considerable effort in the development of a reliable Faraday cup and a Capacitive probe. With these two diagnostics we can measure the local beam current density and the overall charge neutrality of the beam. In our normal mode of operation we bias the

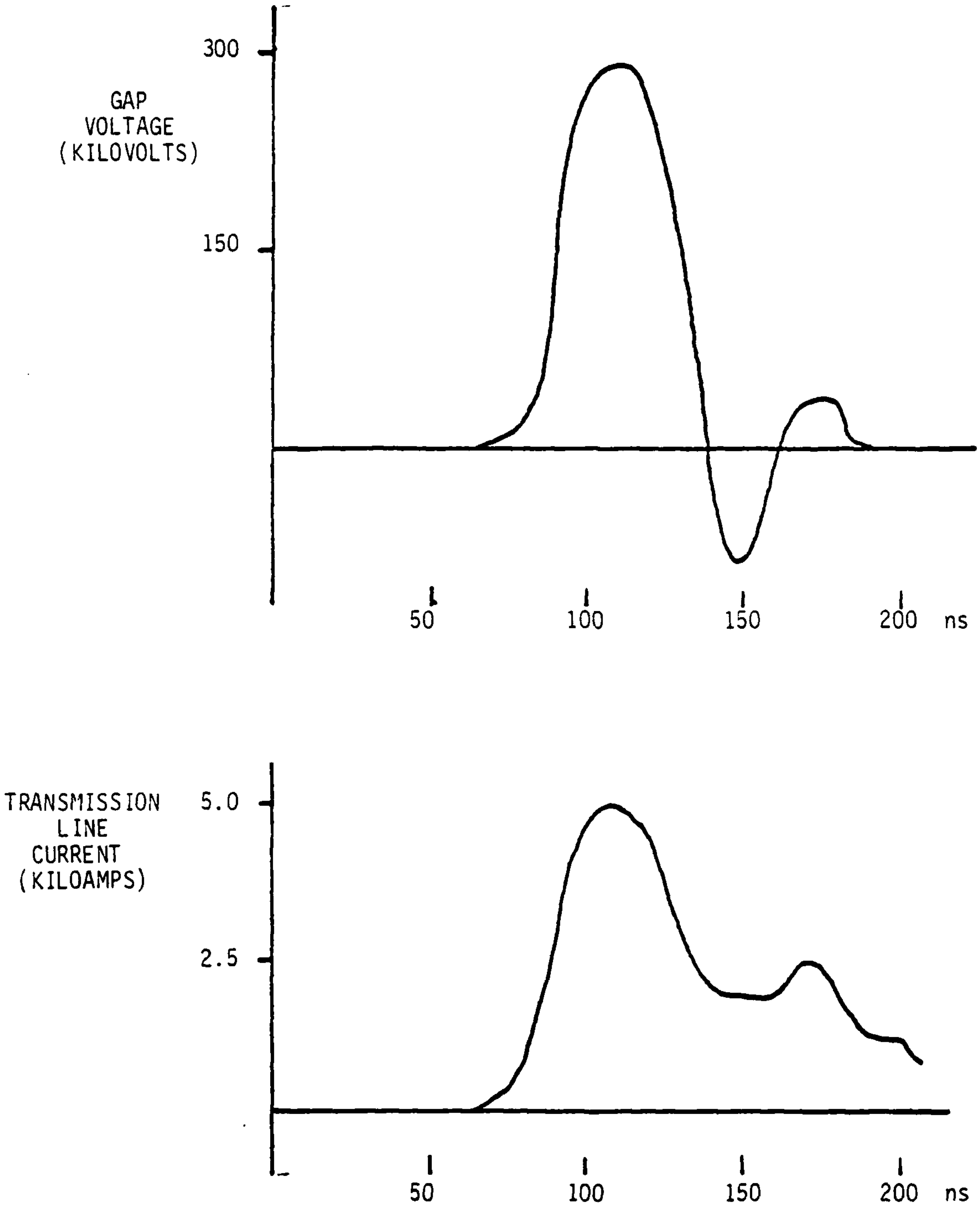

FIGURE 3

POST ACCELERATION GAP VOLTAGE AND CURRENT

Faraday cups to retain any secondary electron emission. In this mode the cup measures the local net current density comprised of the currents due to the drifting protons and the codrifting electrons which charge neutralize the ion beam. Specimen signals from both detectors are shown in figure 4. Accompanying these two traces are representative pulses from the injector system showing the source voltage and current pulses. Note that for part of the pulse duration the Faraday cup shows negative going signals indicating that the electron current density exceeds that due to the positive ions. We are continuing the development of Faraday cups in an effort to devise a system which can be used satisfactorily to measure separately the ion and electron current densities. The measurement of the ion current density is particularily difficult since suppression of the co-drifting electrons by a DC bias field leads to an augmented secondary emission from the probe. The capacitive probe consists of an annular metallic ring located outside of the beam. It is separated from the grounded wall of the drift region by a thin sheet of Teflon. The probe then capacitively divides the beam space to the drift tube wall potential and hence gives a direct measure of the charge neutralization of the beam. Results from this probe show that the beam is typically better than 98 % charge neutral. The probe design includes an upstream annulus located so as to prevent any direct bombardment of the capacitive monitor by the protons or co-drifting electrons. A correction for the effect of this shield on capacitive division has been made using a Poisson solver code. In parallel with this development, work is proceeding on the use of a fluorine prompt gamma detector to determine the beam energy and the dispersion arising from time variations in the beam energy,

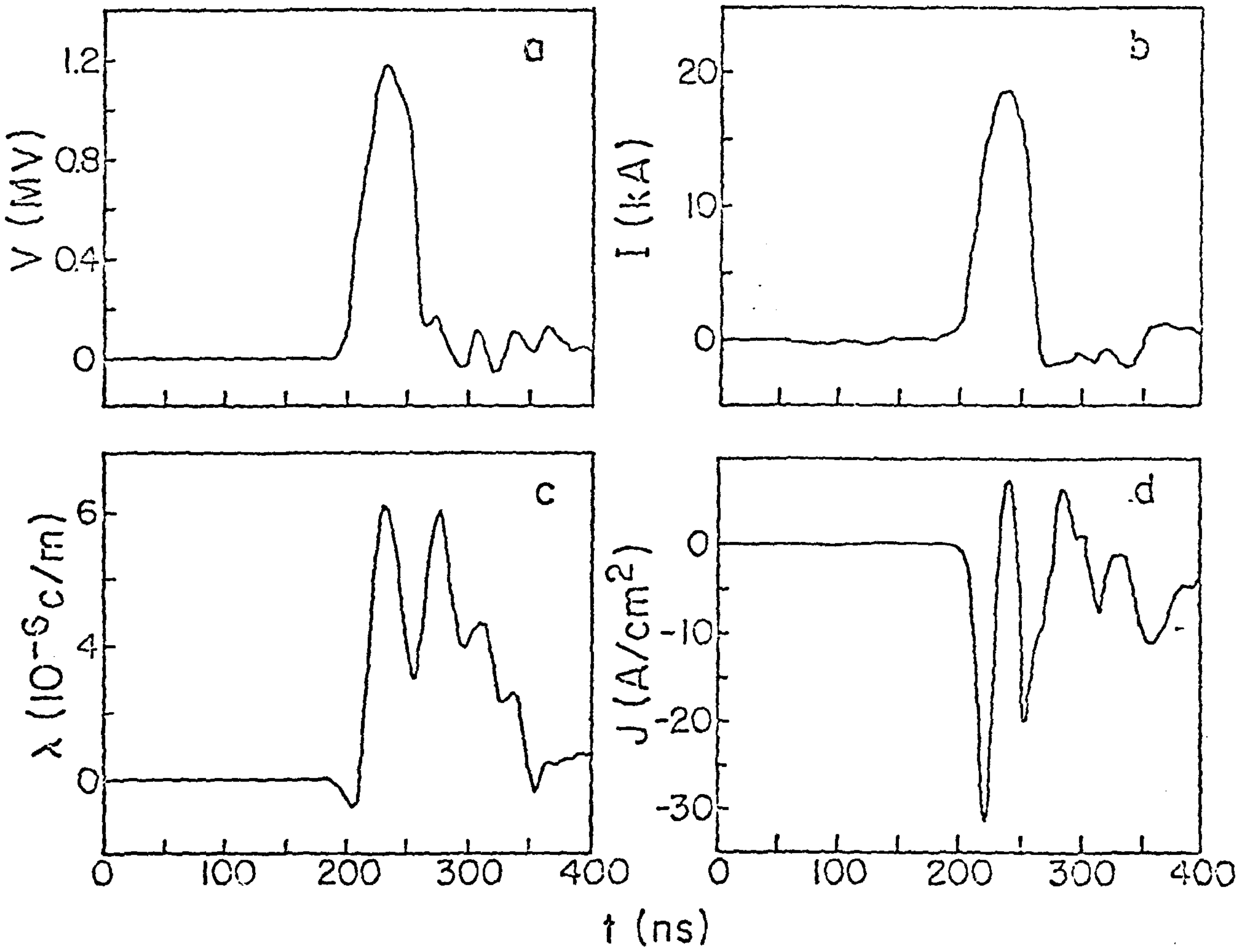

FIGURE 4. BEAM WAVEFORMS

(a) diode voltage

(b) diode current

(c) capacitive electric field monitor

(d) Faraday cup

and on chrome plated plastic scintillators for the measurement of proton divergence. Work has continued on the use of carbon and nickel activation to determine the radial distribution of the protons in the ion beam and to identify the peak ion energy from the nickel activation. A substantial data base is now available using these diagnostics.

C. Proton Beam Generation and Propagation.

At the end of the prior contract period we identified the physical cause of our then low efficiency injector. Substantial electron flow across the diode resulted from azimuthal asymmetries in the magnetic field. This effect was eliminated by improved design of the field coil system, albeit at the cost of increased inductance in the coils and hence a slower field rise time and an enhanced diffusion of the field into the anode. Several diode geometries, each with a good azimuthal symmetry, were tested and the one shown in figure five was adopted. The magnetic field configuration, which was calculated using the MSUPER code, is also shown in the figure. The axial field reaches a maximum value of 20 kGauss and the radial field, under these conditions, is about 10 kGauss at the outer edge of the fin structure. This field is 2.5 times the critical field for magnetic insulation at the diode operating voltage of 1.1 MeV. An immediate result of the change to this new geometry was an increase in the diode proton current to a value of 6 kAmps, a value six times greater than than originally projected for the experiment! The proton current density in this case was found to be 90 A/cm . This estimate is based on carbon activation measurement and an assumed diode proton current time history matching that of the total diode current. In practice the proton pulse does not turn on instantaneously and the peak

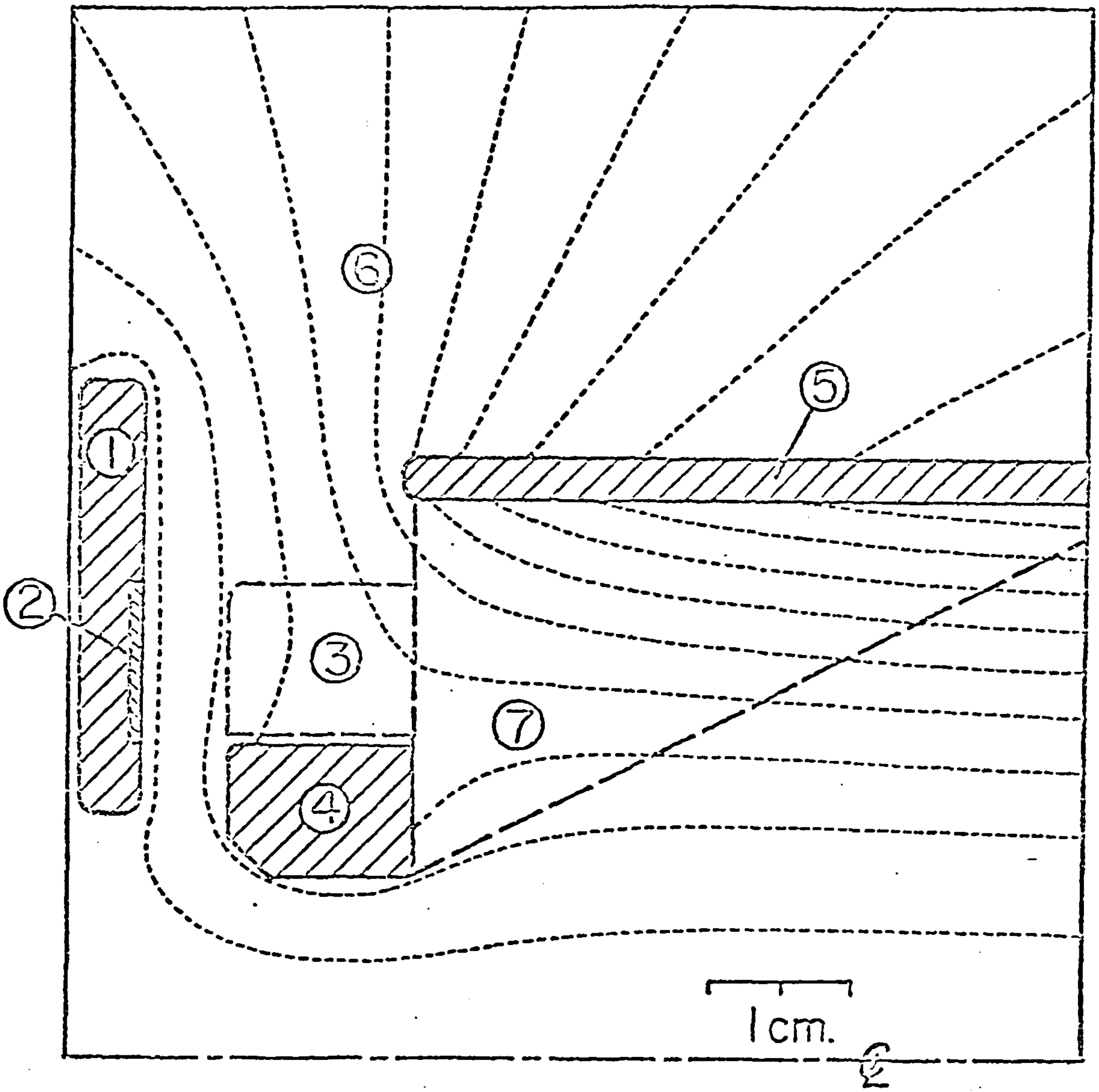

FIGURE 5.

FIRST STAGE AND TRANSPORT SECTION OF A HIGH CURRENT ION INDUCTION LINAC

PROTON ARE EMITTED FROM ACTIVE AREA (2) OF ANODE (1) OF A MAGNETICALLY INSULATED DIODE. THE MAGNETIC FIELD (6) IS PRODUCED BY WINDINGS (4,5). SPACE CHARGE NEUTRALIZATION OF THE BEAM IS ACHIEVED BY ELECTRON FIELD EMISSION FROM METALLIC FINS (3).

current density is greater than quoted. Details of the beam transport found in this configuration are presented in the appended paper entitled, "High current ion beam generation and transport system". It is of interest to note that the ion beam transport is occurring under conditions well above the limit set by space charge for propagation of an unneutralized proton beam. The operating conditions here are probably the closest yet reported to those required for the final transport stage of a heavy ion inertial confinement fusion reactor (i.e. the total charge carried at the set value of the relativistic energy factor, gamma). The beam transport is, as reported, quite efficient and qualitatively as expected for a heavily space charge neutralized beam. The beam focussing arises from the conservation of canonical angular momentum. If we recognize that the protons are born at the surface of a field exclusion anode then the focussing force must be present in the uniform field region. There is still an incomplete understanding of the focussing action since it is not clear how the electrons producing the charge neutralization can cross the magnetic field lines. An interesting aspect of these experiments not reported in the Applied Physics Letter is the observation of an annuler electron beam found in low proton current (< 1kA) operation. The electron ring has a diameter approximately equal to the inner diameter of the inner field coil. Measurements indicate that the electrons have an energy of order 100keV. At the end of this contract period the origin of this beam, which flows parallel to and coaxial with the proton beam, was not clear. The beam is not evident at the end of the drift space in the high proton current experiments. It seems possible that the presence of the beam will enhance the focussing action and may play an integral

role in determining the beam dynamics. Work is continuing in the current grant period in an attempt to understand the physics of this process so that it can be exploited in controlling the beam dynamics in a multi-stag accelerator.

As indicated earlier the second stage of the accelerator was fabricated, assembled, and first tests were carried out on the system prior to the end of the grant period. In this experiment the longer drift space needed for the experimental arrangement meant a reduction in the applied magnetic field strength. To partially compensate for this a new drift tube assembly, with new field windings, was fabricated on a 12.5 cm diameter tube. This tube is 2.5 cm smaller than that used in the experiments described above. We have obtained on indefinite loan from Los Alamos additional capacitors to provide the required magnetic fields. This new capacitor bank has not yet been assembled. In spite of the reduced size of the drift tube the field available is about 20 % lower than that used in the earlier experiments. At the end of the grant period we had vacuum tested the two stage system, checked the field coil operation, and fired the first few shots to confirm the electrical integrity of the device. Current and voltage oscillograms showing the operational characteristics of the post acceleration gap have been shown previously. Nuclear activation using carbon and nickel targets downstream of the post acceleration gap confirmed particle flow across the cusp magnetic field used to insulate the gap. The nickel measurement confirmed that the protons were accelerated across the gap by the induction field since the threshold value of proton energy for the nickel activation could only be reached if more than 100keV was added to the protons by

the second gap. Work will continue on the characteristics of the two stage system in the present grant period.

III Publications and Presentations made arising from work carried out in the Grant period.

Publications.

1. Generation and Control of Charged Particle Beams using Induction Accelerators. Proc. of 5th International Conf. on High Power Particle Beams. pg 493, San Francisco 1983

2. High Current Ion Beam Generation and Transport System. Appl. Phys. Ltrs. 46(3),251,(1985) (Submitted Sept 1984)

Presentations

"Industrial Applications of Intense Beams" Presented at Alcoa Technical Center, PA. November 1983

"Intense Particle Beam Accelerator Research at Cornell University" Presented at Los Alamos National Laboratory, Los Alamos, New Mexico, May 1984.

"An Electron Beam Auto-Accelerator", Bull. Am. Phys. Soc. 28(8),1146,(1984).

GENERATION AND CONTROL OF CHARGED PARTICLE BEAMS USING INDUCTION ACCELERATORS

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Abstract

Investigations have been carried out into the use of Induction Linacs for the acceleration of proton beams. A 1.5 MeV, 2 kA, 30 nsec beam has been generated using an inductively fed magnetically insulated diode. Results will be reported on propagation with and without collective focusing of the beam.

A program to study autoacceleration techniques for the production and time compression of high energy beams has been started recently. A ferrite loaded cavity was used to couple energy from the beam to a 70 ohm transmission line and, after a predetermined delay, back to the beam. Initial experimental results demonstrating particle acceleration and pulse compression will be presented.

Introduction

The Induction Linac accelerator research program at Cornell University has two main elements:
(i) A study of the physics of a high current proton induction linac and,
(ii) An investigation of techniques for the temporal modulation of the beam energy and current.
The first problem under investigation is the efficient generation of a multikiloampere, megavolt proton beam in a magnetically insulated diode, and its transport over length scales commensurate with the employment of a multi-cavity accelerator.

The second aspect of our investigation deals with the autoacceleration of an electron beam in transport through a ferrite loaded induction accelerator cavity. The beam return current loops the ferrite cores, and hence couples power from the beam to a short length of transmission line. The system has been used in two different modes. We have demonstrated the recovery of beam energy by coupling the beam power through the ferrite and transmission line to a passive load at the end of the line. In addition we have made first meaurements of autoacceleration of the electrons in the system by terminating the transmission line in a short circuit. The energy recovery mode is of considerable interest as it provides a practical demonstration of a way to increase the efficiency of a number of collective devices such as the free electron laser.

In the following sections we shall report experimental results obtained with both devices.

Proton Induction Linac Research

We have recently reported progress in this area and will only present a very brief update of this investigation [1]. Figure 1 shows two of the configurations used in the study. The upper part of the figure illustrates the geometry successfully used for the efficient magnetic insulation of the induction linac diode [2]. This configuration was found to produce proton beams with a very high efficiency (an ion to total diode current of order of 75%); the transport of the beams was however poor. We have recently tested a series of diode and transport field geometries, the most recent of which is shown in the lower part of the figure. The main feature of this system is the rapid transition from a magnetically insulating diode to a homogeneous axial guide field suitable for the collective focusing [3,4], and hence efficient transport of the beam. We have found that it is important to minimize the radial return magnetic field crossed by the beam after extraction from the diode. Experimental observations made, using carbon activation techniques, show an increase in the beam transport efficiency when the beam does not have to cross magnetic field lines. Similar results have been found in other studies at Cornell where the effect of the return field on the beam scattering angle of the protons has been measured, and found to increase rapidly in propagation through the return field region [5].

To date we have used the new geometry in a series of low energy ($\lesssim$700 keV) tests. The magnetic insulation has been found to work satisfactorily although at a significantly lower ratio of ion beam current to total current than that found earlier for the upper field geometry system. Measurements at the exit plane of the diode indicated that the ion current distribution, at the one kiloampere current level, had substantial (~3:1) azimuthal asymmetries which varied in both magnitude and location on a shot to shot basis. The data suggested that both the anode turn on and the beam neutralization were marginal at the operational levels. The less satisfactory operation may be associated with a greater degree of asymmetry in the diode magnetic insulation field than that found in the original geometry of Fig. 1a. A calculation of the radial electric field associated

with a one kiloampere unneutralized proton beam entering the drift tube along the axial guide field, shows that the surface field at the drift tube walls would be less than 100 kV/cm. This is marginal for the emission of the electrons required to neutralize the space charge of the proton beam. It seems that it is probably important to form a well defined virtual cathode surface capable of providing all of the electrons required to neutralize the proton beam space charge. It would also seem desirable to increase the proton current density so as to ensure beam neutralization from the walls of the system. Failure of both of these processes would necessitate the use of an externally driven source of electrons for beam neutralization. We are presently in the process of testing the new geometry at higher voltage and at greater current densities to establish the prospect for good beam transport without the addition of externally driven ion neutralization sources. The role of asymmetries in the diode fields is also being studied.

Autoaccelerator Research

Autoacceleration of high current electron beams has been investigated in a number of laboratories [6,7]. In this investigation we describe research carried out into the use of passive ferrite loaded induction accelerator systems for the acceleration and pulse shaping of electron beams. An advantage of the ferrite loaded autoaccelerator over those using coaxial vacuum cavities is that the flux is concentrated in the ferrite, hence it is possible to produce uniform acceleration fields on the charged particles, independent of their radial location in the accelerating gaps. It is also possible to make compact systems, and to readily change the parameters of the system, e.g., the electrical length or the impedance of the transmission line used for coupling the energy to and from the beam.

The autoaccelerator system used in this work is sketched in Fig. 2. It consists of an oil insulated, ferrite loaded, cavity containing either 6 or 9 TDK P14 ferrite cores. The cores are driven from their remnant magnetization state to saturation in the reverse sense by the field associated with the current in the beam-return conductor circuit. A secondary circuit links the cores, coupling a fraction of the beam power to a 70 ohm oil filled transmission line. A variety of transmission line lengths have been used, having electrical lengths corresponding to pulse round trip times ranging from 17 to 35 nsec. Most of the work described here was carried out with a nominal 28 nsec round trip time cable. The ferrite used had a flux swing of 0.025 Vsec. A 5-6 kA, 800-900 kV annular electron beam was generated in the diode. The diode configuration employed produced a 4.0 major diameter, 0.1 cm minor diameter electron beam. The beam propagation was controlled by a strong axial magnetic field. The parameters used in this initial study were chosen so that the beam was at all times far from the limiting current of approximately 18 kA in the short first section of drift tube. The diagnostics employed in the experiments included measurements of the:

(i) Beam injection energy and current,

(ii) Time resolved thick target x-ray yield in the forward direction,

(iii) Transmission line current and,

(iv) The autoaccelerator gap voltage.

Figure 3 shows data typical of the results found for this system. Representative oscilloscope traces showing the autoaccelerator gap voltage, the transmission line current, and the x-ray monitor output are shown in the figure for three sets of conditions corresponding, from left to right to:

(i) The autoaccelerator gap shorted at the grading rings. In this condition we only have an x-ray output pulse. The accelerator gap spacing of 5 cm was set to maintain the same x-ray signal with the target in front of and behind the gap.

(ii) The beam energy was coupled through the ferrite to the transmission line, which in turn was terminated in a resistive load of approximately 40 ohms.

(iii) The configuration is identical to that used in (ii) with the exception that the transmission line is terminated in a short circuit. Immediately below these records are traces illustrating the injected beam current and voltage.

In the resistive load case we observe that the transmission line current of about 6 kA is somewhat greater than the measured beam current, as a result of the load impedance being smaller than the characteristic impedance of the cable. The x-ray monitor shows a substantial decrease in amplitude reflecting the loss of beam energy. The increase in the x-ray signal amplitude towards the end of the pulse is associated with reflection of the wave from the load at the end of the line. Based on the measured beam and transmission line parameters we find that we have in this case recovered one-quarter of the beam energy into the load at the end of the line. With a matched load we have demonstrated recovery of more than half

of the beam energy. It should be noted that these figures for the energy recovery do not indicate limits on efficiency. We expect to operate at much greater efficiency as the current is increased towards the limiting value, or as the line impedance is increased at fixed beam current.

In the final case illustrated we see that the autoaccelerator gap voltage changes sign in the middle of the pulse and that the x-ray output pulse is characterized by a rapid increase to a value considerably in excess of its initial amplitude. The x-ray output in the latter half of the pulse is also greater than that found in the case where the autoaccelerator gap was shorted indicating the increase in beam energy as a result of the autoacceleration process. A substantial change in the transmission line current is also evident. This current reaches a peak value of 9.5 kA, more than 50% greater than the injected beam current. The large value of the line current was determined by current doubling on reflection from the short circuit at the end of the line.

Figure 4 shows data obtained with different length transmission line sections. In the first case the round trip time on the line was reduced to 17 nsec and in the second case it was increased to 35 nsec. In both cases we show the autoaccelerator gap voltage and the x-ray yield from the electron beam hitting the thick target following autoacceleration. The change in pulse duration is apparent. In addition to the pulse duration changing, the effect of the pulse rise time compared to the transmission line round trip time is evident. Clearly for efficient autoacceleration it is necessary that the rise time of the pulse be short enough compared to the propagation time on the transmission line.

It is possible to describe the results obtained in terms of a simple transmission line model in which the primary beam energy is coupled to a lossless transmission line. The boundary condition at the beam is that of a current source. The effect of this is to produce a current pulse cancellation at the beam end of the line. This leads to a criterion for power flow from the line to the beam, namely that the current pulse, reflected from the short circuit at the end of the autoaccelerator line, exceeds 50% of the instantaneous beam current. This is seen experimentally as a reduction of the autoacceleration gap acceleration voltage with the short transmission line compared to that found in the longer line cases. The time taken to reverse the sign of the autoaccelerator gap voltage is greater than that predicted by the model. This is probably due to the frequency response of the ferrite. Inclusion of a 15 nsec rise time for the ferrite leads to waveforms approximately consistent with the experimental results. Figure 5 shows the output from the model for the 35 nsec transmission line. The curves shown represent the x-ray yield and the autoaccelerator gap voltage. These results have been obtained using the actual beam current and injection voltage waveforms and artificially increasing the round trip time to 50 nsec. A more detailed modeling including allowance

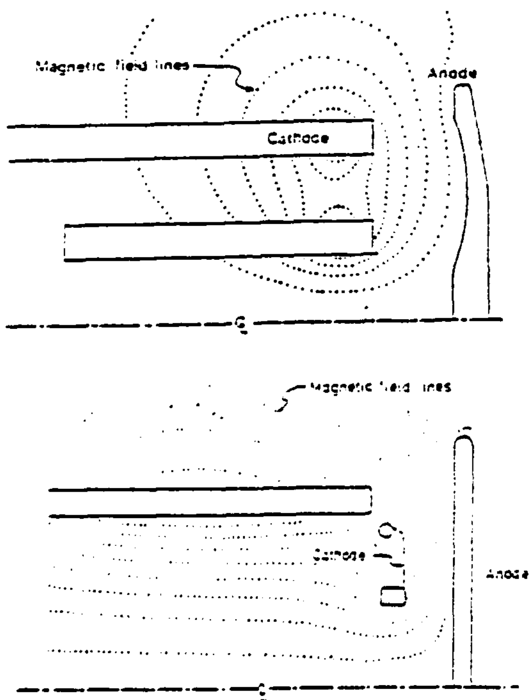

Fig. 1 Diode configurations used in proton inductive linac study.

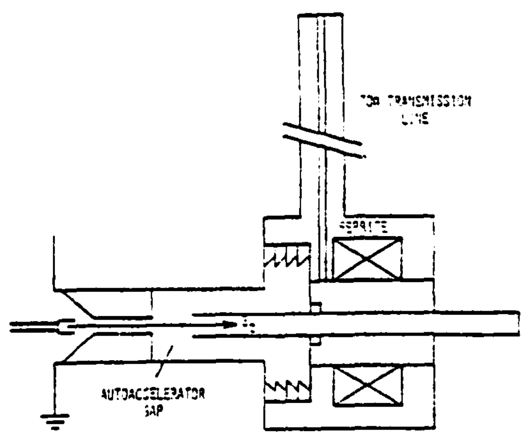

Fig. 2 Autoaccelerator schematic diagram.

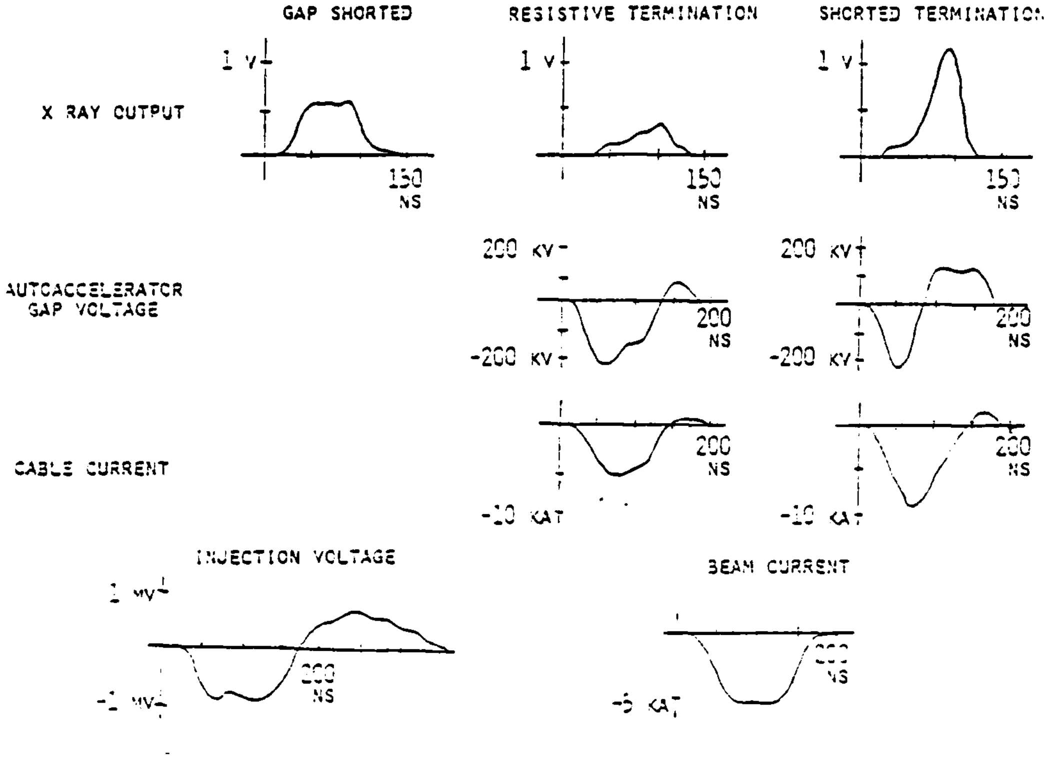

Fig. 3 Representative oscilloscope traces of autoaccelerator.

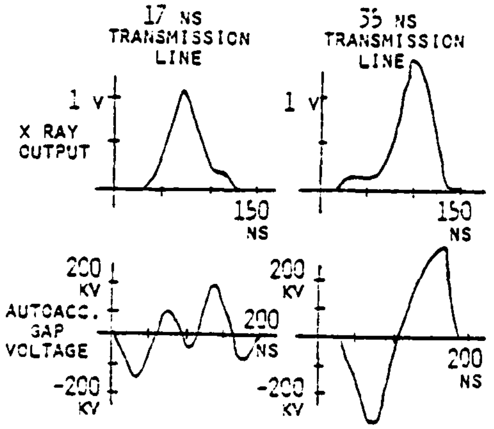

Fig. 4 The effect of transmission line length on x-rays and gap voltage.

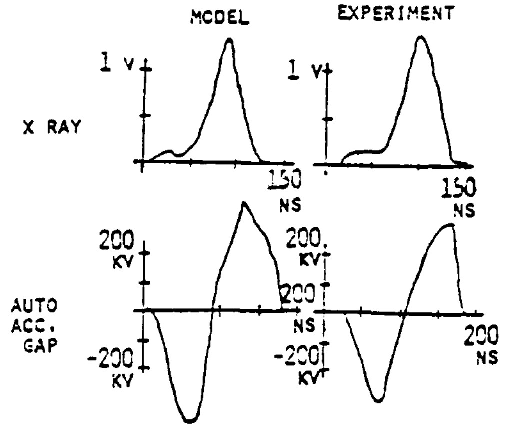

Fig. 5 Comparison of computed and experimental results.

of the transfer function of the ferrite transformer is in progress. The finite rise time effect of the ferrite cores will also reduce the computed output beam energy.

Acknowledgements

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High current ion beam generation and transport system

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The efficient transport of a 6.0-kA, 1.1-MV proton beam generated in a magnetically insulated diode and propagated along an axial magnetic field has been studied. The beam is better than 98% charge neutral. Focusing of the beam is observed as a result of beam transport through the radial magnetic insulation field. The application of this type of beam generation and transport system to a high current linear induction ion accelerator is discussed.

Until recently, high current linear induction accelerators have been used solely to drive electron beams.[1-6] If induction accelerator techniques can be applied to the generation of mulikiloampere, multimegavolt ion beams, then these beams would find applications in inertial[7] and field reversed magnetic[8,9] confinement nuclear fusion, and neutron production. We examine, in this letter, a technique for the production of such beams. Any practical device must solve several problems including (1) inhibiting electron flow in the accelerating diodes so that power is primarily coupled to the ions, (2) charge neutralizing the beam in the drift region separating acceleration gaps so that the radial electric field of the non-neutral ion beam is reduced to a level which allows beam propagation, and (3) radially confining the beam inside the accelerator.

In this letter we present results showing that it is possible to satisfy the above conditions so that a multistage ion accelerator might be developed.

The diode and drift tube configuration used in these experiments is shown in Fig. 1. The coils are wound with 12-gauge, 600-V insulated wire covered with fiberglass braid. The turns are helically wrapped on 0.16-cm-thick stainless forms, and are covered with fiberglass cloth and epoxy. The turns are immediately adjacent to each other, so the helical pitch is the wire thickness, 0.37 cm. Four 0.32-cm-thick stainless steel struts, 10 cm long at the outside edge, support the inner coil.

The magnetic field produced by the coils suppresses electron flow in the diode. The magnetic field lines shown in the figure are calculated using the program RSUPER,[11] approximating for the penetration of the 2-ms rise time magnetic field into a 1-cm-thick copper anode. Since electrons are free to flow along field lines, the field lines are equipotentials and the electric field in the diode is nearly axial. The electron emission needed to define the equipotential surfaces and to produce anode flashover comes from four radial fins attached to the support struts. At the outer edge of the fins the magnetic field is 1.0 T. For a diode voltage of 1.1 MV and an acceleration gap of 1.3 cm this is 2.5 Bcrit,[12] where Bcrit is the field strength required to suppress electron flow in a planar diode. The direction of the magnetic field makes a sharp transition downstream of the diode to an axial field of value 2.1 T. Protons forming the beam are emitted from an epoxy surface in the anode embedded with metal pins.[13] The azimuthal velocity the beam acquires as a result of crossing magnetic field lines, combined with the axial magnetic field, causes a radial inward force. This differs from the Pulselac experiment[14] where the beam is ballistically focused by the electric fields in the accelerating diodes. Note that neutralizing electrons can flow from the diode along field lines into the drift region.

Diode voltage and current are shown in Fig. 2(a) and 2(b). The proton current is approximately 30% of the total diode current. X-ray pinhole pictures were taken of the bremsstrahlung coming from the anode, an indication of electron bombardment and hence of diode uniformity. The photographs, which have insufficient contrast to permit reproduction, indicated the need for good azimuthal uniformity in the magnetic field so that $\nabla B \times B$ drifts do not cause early diode closure.

The $C^{12}(p,\gamma)N^{13}$ reaction[15] was used to determine the beam profile and transport efficiency. Figure 3 shows the proton beam density at various axial positions. The propagation efficiency in the system was measured by placing four graphite targets at the front of the region over which propagation was to be measured, and an x-shaped array at the back. The transport efficiency of the beam over the first 19 cm of the experiment was only 75% due to losses to the support struts and the proximity of the beam to the drift tube wall. However, as the beam propagates it detaches from the wall, and over the last 27 cm the efficiency was 93%. In both cases the estimated accuracy of the beam transport efficiency measurement was 10%. The losses could be reduced further by increasing the spacing between the beam and the drift tube. The losses here are much smaller than those reported earlier[16] in a geometry where the ion beam had to

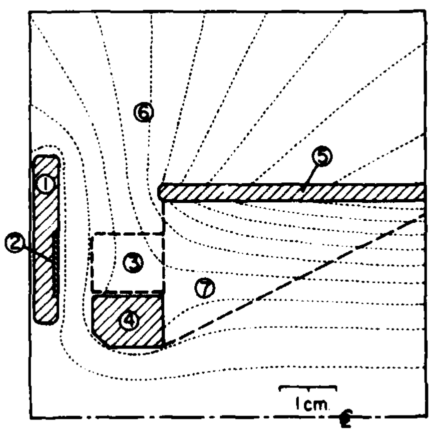

FIG. 1. Diode and drift tube. (1) Anode, (2) proton emission surface, (3) electron emission fins, (4) inner field coil, (5) outer field coil, (6) magnetic field lines, (7) support struts.

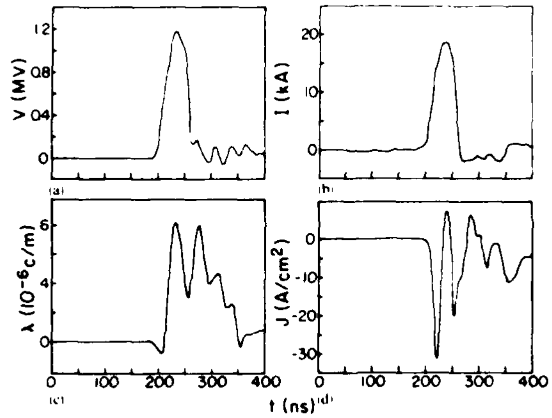

FIG. 2. (a) Diode voltage, (b) diode current, (c) capacitive electric field monitor, and (d) Faraday cup.

propagate through the return field lines associated with the magnetic insulation field.

The activation results show that there is some focusing of the ion beam. The first protons reach the axis at about 19 cm past the anode. (The single particle focal length is 23 cm.) However, the distribution does not come to a sharp focus, and much of the ion current continues to flow near the outside edge of the beam. In the region from 2.5 to 4.1 cm radius the inner field coil blocks access of electrons from the diode. As the beam passes through this region the space charge produces a radial electric field. This field retards the focusing. For radii less than 2.5 cm, electrons in the diode can readily neutralize the ion beam.

The proton beam current, based on the carbon activation measurement and the pulse shape of the diode current, is 6 kA. This gives an injected current densityof 90 A/cm^2. Current due to other ions is not measured by activation procedure used. In addition, carbon activation was used to measure the width of the beam edge. The scale length is typical of the gyroradius of a proton with a transverse energy of about 50 keV.

The radial electric field at the drift tube wall was also measured. The electric field probe[17,18] was located 25 cm from the anode. It consisted of a 1.3-cm-wide tube of stainless steel insulated from the drift wall by a 0.025-cm-thick teflon sheet 4 cm wide. The probe was shielded from beam bombardment by a 1.5-cm-wide annular shim at the upstream edge of the teflon. Calculations show that this shim reduces the electric field at the probe location by 14%. The *RC* time constant of the detector was chosen to be much longer than the pulse width. The peak unneutralized charge in the beam is 8×10^{-6} C/m, based on the assumption of a long beam. The 6-kA, 1.1-MV beam is therefore 98% charge neutral. A Faraday cup, biased on + 100 V to suppress secondary emission, was also used. Traces from the two detectors are shown in Figs. 2(c) and 2(d). The Faraday cup shows a peak local magnetic neutralization of about 150% indicating the electrons are moving faster than the protons.

The ions are radially confined in the axial field as a result of the charge neutralization and the focusing action of the radial magnetic field in the diode. It is unlikely that the proposed collective confinement of the beam,[19] similar to collective focusing,[20] is important in these experiments since

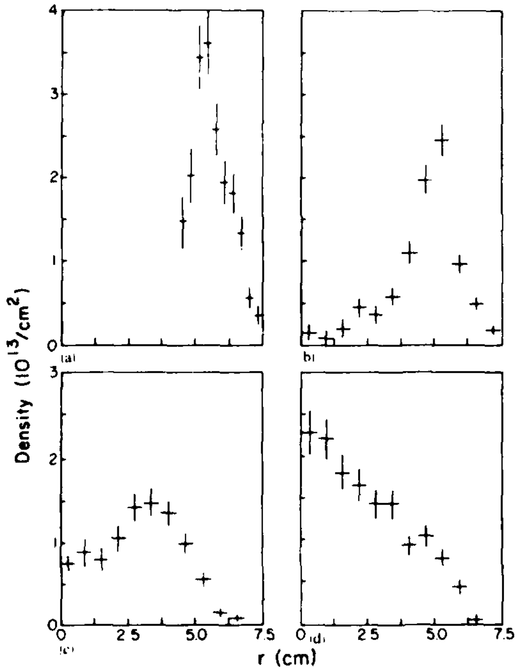

FIG. 3. Proton density as a function of radius for different axial positions: (a) 5 cm from anode, (b) 19 cm from anode, (c) 34 cm from anode, and (d) 46 cm from anode.

the radial electric field measured by the capacitive probe is outward rather than inward. A confining sheath implies that the beam region is at a negative potential with respect to the tube walls. This cannot occur in these experiments since the neutalizing electrons are emitted from a surface at ground potential.

The propagation described here could conceivably be extended to a multistage system if inner field coils, which would cause substantial beam loss, are not required in subsequent stages. An inner coil was used in the diode described here because the virtual cathode formed in a half cusp is defocusing. However, additional gaps would be magnetically insulated by a full cusp, and the convex equipotentials would tend to focus the beam.[21]

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